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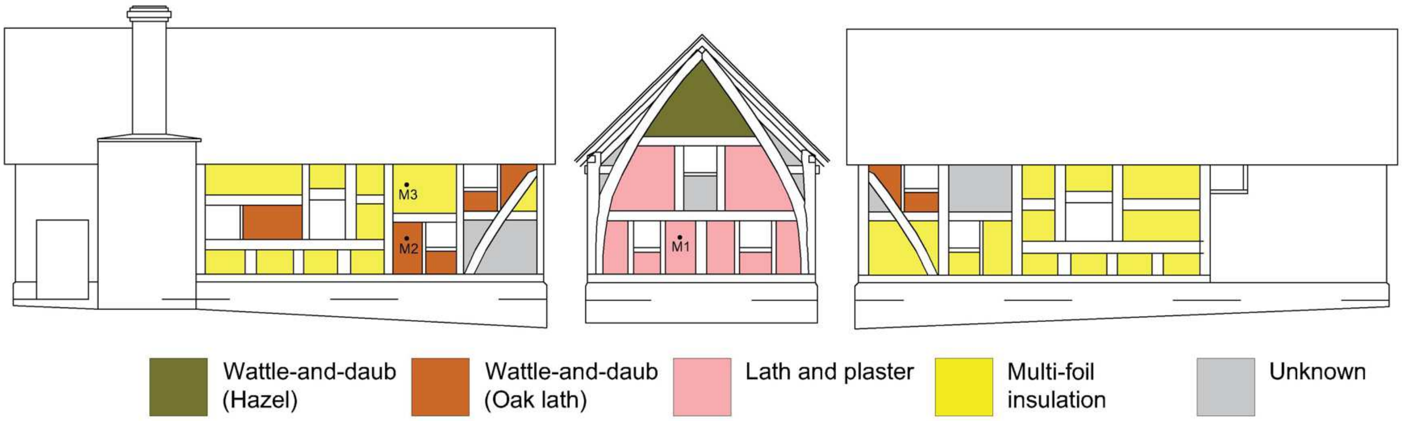

Fig. 1. Hacton Cruck Hall, east, north, and west elevations showing panel infill materials, 2015. All images by the authors, unless otherwise noted.

Monitoring timber-framed buildings reveals the importance of a holistic approach when considering their retrofit.

With dwellings now responsible for 37 percent of the final energy use in the UK, the demands placed on the performance of domestic building envelopes are increasing.[1] Centuries-old walls of heritage buildings are now the focus of energy retrofits that aim to reduce greenhouse-gas emissions, lower energy bills, and improve hygrothermal comfort. Understandably, research in the UK to date has focused on the retrofit of solid masonry construction, which accounts for 93 percent of the pre-1850 building stock in England.[2] However, retrofits in the UK are also being undertaken on some of the 66,000 pre-1850 timber-framed buildings, but with only limited knowledge of the impact of the applied solutions. In order to ensure their preservation, it is essential to understand the thermal performance of the constituent elements of these buildings and the potential impact of introducing new materials. Failure to do so could result in increased risk of interstitial condensation, raised moisture levels, and irreversible damage to the historic fabric through fungal or insect attack.

This paper presents the results of in situ U-value (thermal transmittance) monitoring of three infill panels of differing ages and material assemblies at a fifteenth-century cruck hall in the Wye Valley in Herefordshire in the English West Midlands. The property, once derelict, has been restored in stages over the past 15 years by its owner and now provides holiday accommodation (Fig. 1). Three types of panels were monitored: one original oak-lath and lime-plaster panel, one replacement wattle-and-daub panel (earth render on timber lath), and one new panel with modern multi-foil insulation consisting of reflective foils separated by polyester fleece. The multi-foil insulation is held in place between vertical timber staves within a void finished internally and externally with lime plaster on expanded metal lath. Figure 1 shows the location of each panel type and the monitoring points M1, M2, and M3. Twenty-two percent of the infill panels are original oak lath and lime plaster; 18 percent are wattle and daub; 46 percent are insulated; and 14 percent are of unknown construction. All panels are visually identical and in good condition. Thermography and pressure testing were also conducted to complement the in situ U-value monitoring. This monitoring forms part of an ongoing PhD research project into the low-carbon retrofitting of historic timber-framed buildings in the UK.

Cruck Construction

Evidence of cruck construction can be found in the British Isles dating from at least the twelfth century; it is argued by some to have pre-Roman origins.[3] The technique utilizes pairs of massive, book-matched timber members cut from the same tree, which rise from low within the external walls to the apex of the roof.[4] Most of the roof loads are carried by these principal members; the walls are secondary elements whose principal role is to enclose the internal space, providing shelter from the elements. The material used in the walls to create this enclosure varies according to geographical region (Fig. 2) with traditional materials including stone, brick, timber frame, and cob. The variation in infill material is most probably due to the influences of climate and availability of local materials. The distribution of external wall materials illustrated in Figure 2 clearly shows the limestone belt, running diagonally from the southwest, that divides the forests of central and southeast England. The preference for stone or brick walls in the west and north of the country could also be due to the harsher climates of these areas.

Hacton Cruck Hall, Preston-on-Wye

Hacton Cruck was constructed as a three-bay, single-hall dwelling in the late-fourteenth or early-fifteenth century.[5] The property was divided into two separate dwellings sometime during the eighteenth or nineteenth century but lay uninhabited and abandoned for much of the twentieth century. Prior to restoration, the south bay had collapsed, and much of the remaining fabric was in a poor state of repair. Over a period of 12 years, starting in 2000, the current owner undertook a process of restoration that resulted in the building that exists today (Fig. 3).

In order to reconstruct the lost south structural bay, it was necessary to relocate the building approximately 30 meters (90 feet) to the east (Fig. 4).

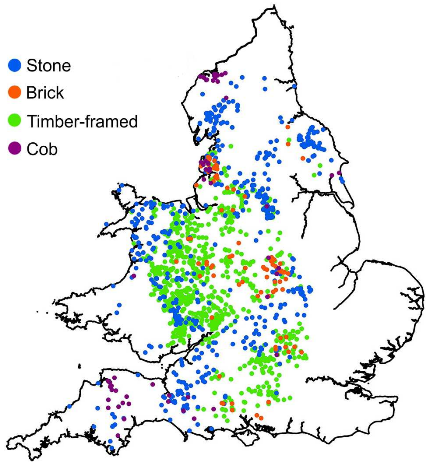

Fig. 2. Map of the UK showing distribution of surviving and demolished cruck-framed buildings according to N. W. Alcock, Cruck Construction: An Introduction and Catalogue (London: Council for British Archaeology, 1981). The map is by the authors based on the information of N.W. Alcock.

Fig. 3. Hacton Cruck Hall, Preston-on-Wye, Herefordshire, UK, built in the late-fourteenth or early-fifteenth century, east elevation looking northwest, 2015.

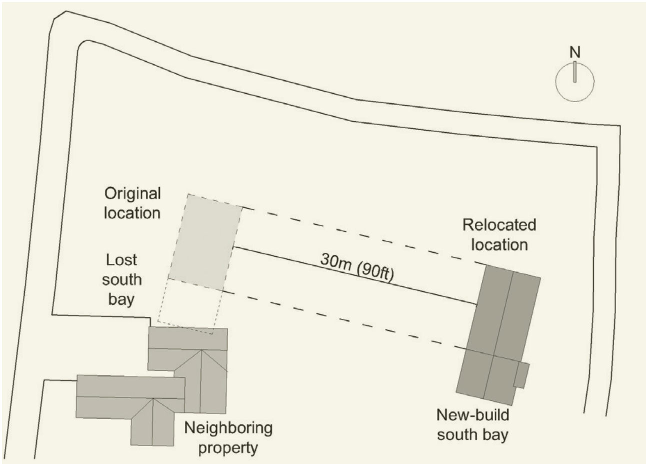

Fig. 4. Hacton Cruck Hall, site plan showing original and relocated site, 2015.

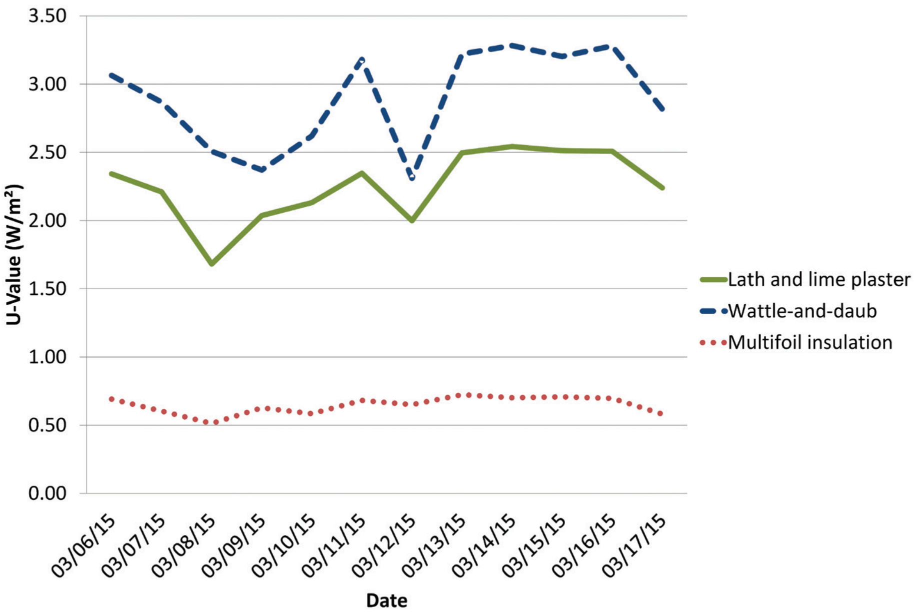

Fig. 5. Calculated U-values of three infill-wall panels measured on March 6–17, 2015.

To achieve this, the timber frame was first repaired in its original location before being hauled across flattened ground by a vintage Matador timber crane. The roof was rethatched, with the thatch being exposed internally in the two-story central bay. Although most of the original infill panels had been lost, those of the north wall survived, protected by a modern lean-to pigsty and weatherboarding above. These surviving panels consisted of lime plaster on traditional riven-oak lath. With minor repair work, all but the topmost panel were saved. Elsewhere, in order to provide improved thermal resistance, most of the new infill panels incorporated multi-foil insulation, sandwiched between finishes of lime plaster on expanded metal lath. In some parts however, the members of the external timber-frame walls were barely 76 millimeters (3 inches) wide; here, new panels of wattle and daub were installed. The presence of these three panel types in one building presented the opportunity to monitor three different constructions under the same climatic conditions. Like much of the UK, the Wye Valley has a temperate-maritime climate with warm summers and cold winters. The heating season typically lasts from November until March with no requirement for mechanical cooling during summer months.

In Situ U-value Monitoring

In order to evaluate the thermal performance of the three different types of panels, in situ U-value monitoring was undertaken during the heating season over a period of two weeks in early March 2015. The methodology employed was in accord with the British Standard BS ISO 9869-1:2014, "Thermal Insulation—Building elements—In-situ measurement of thermal resistance and thermal transmittance. Part 1: Heat flow meter method."[6] The heat flux (W/m²) through each infill panel was measured with a Huxeflux HFP01 heat-flow meter plate connected to an Eltek telemetry transmitter with inputs for voltage. The transmitter in turn relayed the data to an Eltek Squirrel data logger, with the voltage recorded at five-minute intervals. The internal ambient air temperature (˚C) directly behind each heat-flow plate was measured with an Eltek telemetry transmitter with built-in temperature and relative-humidity sensors; measurements were recorded at the same frequency as the voltage. The external ambient air temperature (˚C) was measured adjacent to the external wall surface at the points corresponding to the internal location of the heat-flow plates. The temperature was measured using thermistors connected to an Eltek telemetry transmitter with inputs for external thermistors, also transmitting to the Eltek Squirrel data logger, with readings at the same frequency of five minutes.

Using the data collected, the daily mean U-value was calculated according to the following equation:

$$\text{U–value} = \frac{\sum_n Q}{\sum_n (t_i - t_e)}$$

Where
Q = mean heat flux (W/m²)
t_i = mean internal temperature (°C)
t_e = mean external temperature (°C)

In accordance with BS ISO 9869–1:2014, only nighttime readings (from one hour after sunset until sunrise) were included in order to remove the influence of any direct solar radiation. The thermal conductance was deemed to be that recorded over a period of three subsequent nights, where a variation of no more than ±5 percent was detected in the calculated U-value. This was observed on the nights of March 13 through 16, 2015. The results obtained are presented in Figure 5 and Table 1.

The results show that the original lath and lime-plaster panel performs remarkably well with a U-value equivalent to that of a historic solid brick wall.[7] The new wattle-and-daub infill performs less well, with a U-value equivalent to that of a concrete wall 250 millimeters (10 inches) thick. The new panel with multi-foil insulation sandwiched between lime plaster on metal lath performs the best, with a U-value equivalent to that of a typical new stick-frame building insulated with 2 inches of mineral wool. The new insulated panel conducts only 28 percent of the heat when compared to the original lath-and-plaster panels.

Table1. Thermal transmittance and thermal resistance

Wall panel infill	U-value (W/m²K) (Thermal transmittance)	R-value (hr ft2 ⁰F/Btu) (Thermal resistance)
Lath and lime plaster	2.51	2.26
Wattle-and-daub	3.25	1.75
Multi-foil insulation	0.71	8.0

Table 1. Thermal transmittance and thermal resistance of wall panels calculated from data (shown in Figure 5) measured March 13-16, 2015.

Thermography

At the end of the two-week measurement period, thermography of the property was undertaken using a FLIR thermal-imaging camera. The images were taken at 5:30 a.m., a half hour before sunrise, to ensure maximum temperature differences between the internal (15°C, 59°F) and external environments (1°C, 34°F) and to avoid any influence of direct solar radiation.[8] Additional fan heaters were used for an hour prior to taking the images to achieve this temperature difference. To further enhance the transfer of heat, the building was first pressurized for thermography of the exterior of the building, then depressurized for the thermography of the interior. This was achieved using a Minneapolis Blower Door, a standardized kit consisting of an adjustable fabric door fitted with a variable speed fan.

The images clearly show the differing thermal performance of the various infill panels, with the lighter, warmer colors indicating areas of higher heat loss. In Figure 6 two new wattle-and-daub panels can be identified in paler orange (a and b), due to their higher surface temperature. One panel is located between the two windows on the left (a), and the other is L-shaped and adjacent to the right-hand window (b). Cold-bridging (increased localized thermal transmittance) formed by the upright timber staves within the panels appears as the lighter vertical lines in the middle of each panel. The image also indicates the lack of sufficient perimeter insulation to the edge of the concrete floor slab containing underfloor heating.

While the external thermography visibly demonstrates the differing thermal performance of the infill panels (Fig. 6),

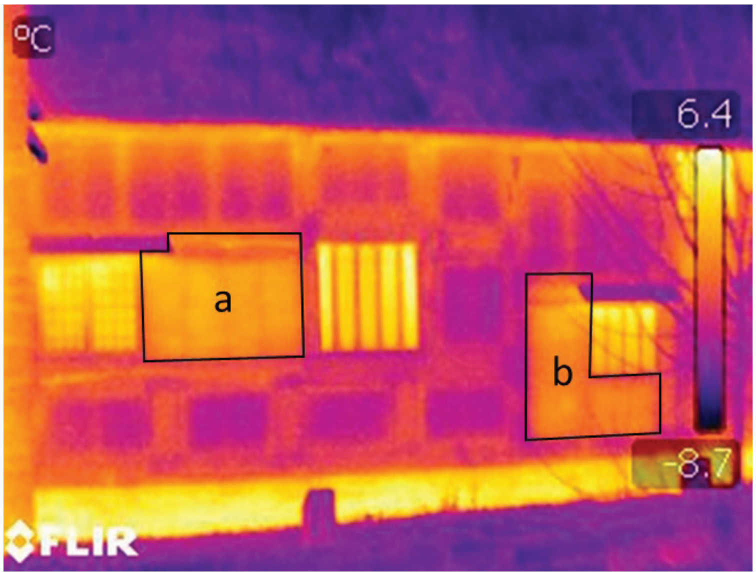

Fig. 6. Hacton Cruck Hall, thermographic image of exterior of east elevation, taken at 5:30 a.m. on March 25, 2015. Lighter colors indicate greater heat loss. New wattle-and-daub panels (a and b) show more heat transfer than surrounding panels insulated with multi-foil insulation.

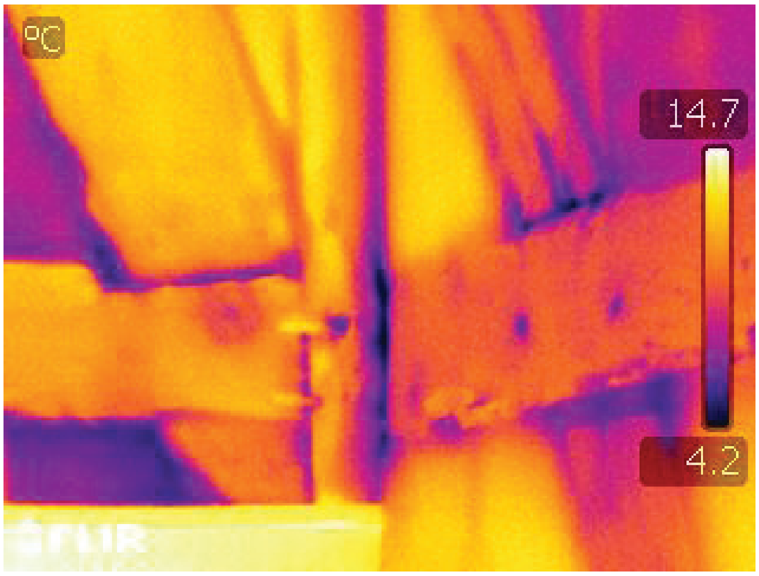

Fig. 7. Hacton Cruck Hall, thermographic image of internal northeast corner, taken at 5:45 a.m. on March 25, 2015.

the internal thermography made evident the heat loss via air infiltration through the perimeter joints between panel and frame, through the joints between timbers, and through peg holes within the timber members themselves (Fig. 7). The cold air being drawn into the depressurized building shows up as dark blue and purple in this image. Overall, the thermography begins to suggest that while the inclusion of multi-foil insulation within most of the new panels will improve their individual performance, there are other factors influencing the overall efficiency of the building as a whole. These factors became more evident in the results of the hygrothermal monitoring and pressure testing.

Hygrothermal Comfort Monitoring

In order to assess the current hygrothermal-comfort conditions (temperature and relative humidity) achieved within the house, TinyTag hygrothermal sensors were mounted in four internal locations and one external location protected from precipitation and direct solar radiation in order to monitor ambient air temperature (°C) and relative-humidity percentage. Although the ISO 7726 recommends that sensors be located at specific heights within the center of the space being monitored, this arrangement was not possible since the property is a holiday rental and there was concern over potential visual intrusion and the risk of interference from guests. It was therefore necessary to locate the sensors discreetly within the four rooms. While this arrangement reduced the accuracy of the readings, it was only by doing so that continual monitoring could occur. Monitoring took place over the period of one year, from March 2015 until March 2016.

The results of this monitoring are presented in Figures 8 and 9. They show the hygrothermal comfort as defined by Baruch Givoni for those days when the house was occupied, according to the visitors' book.[9] The results show that the warmest room in the house is the ground-floor bathroom, which has only one external wall, original lath-and-plaster infill, and underfloor heating. However, due to high relative humidity, this

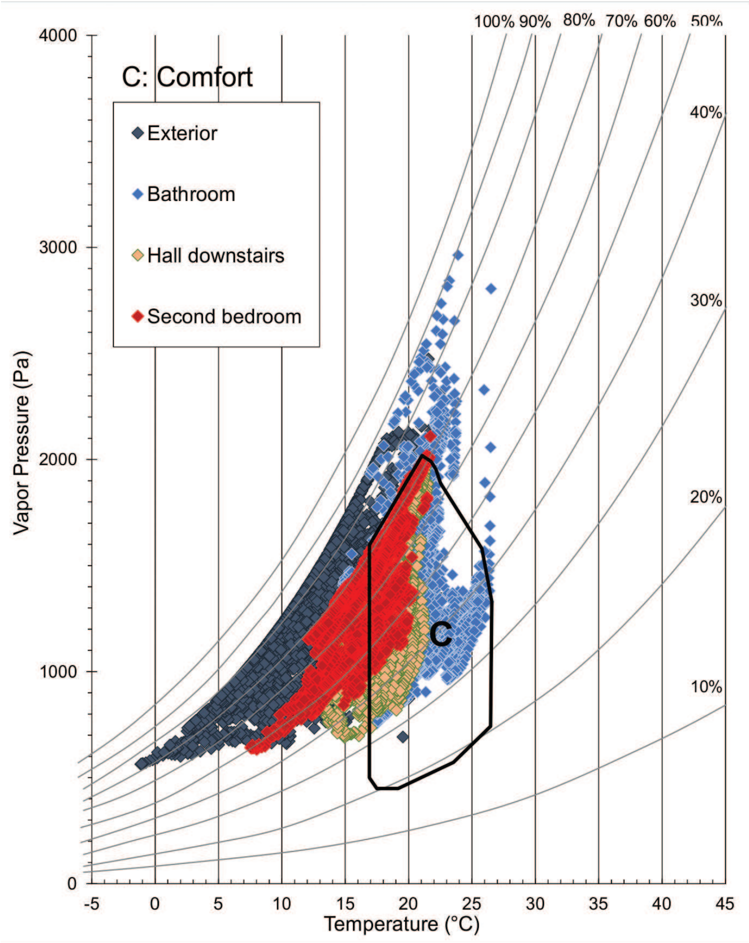

Fig. 8. Psychrometric chart created according to Baruch Givoni showing hygrothermal comfort at Hacton Cruck Hall during occupied days between March and November, 2015.

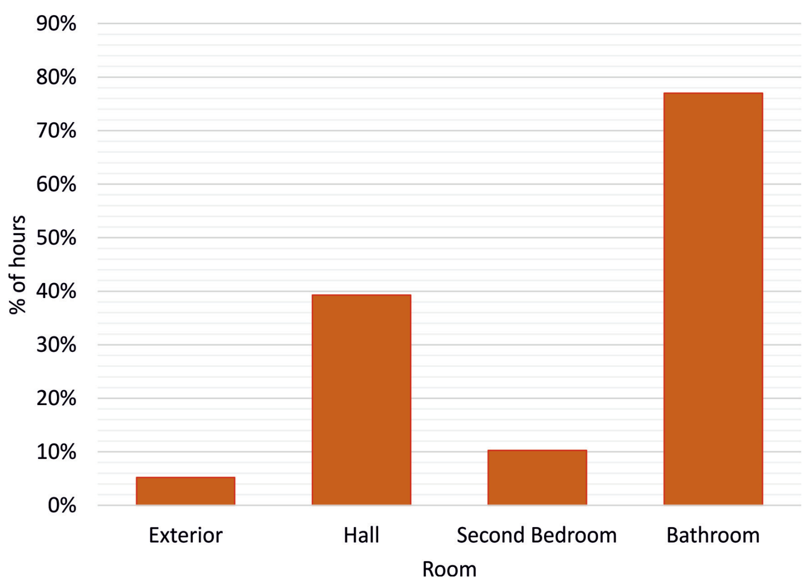

Fig. 9. Percentage of occupied hours where hygrothermal comfort was achieved at Hacton Cruck Hall between March and November, 2015.

room achieves acceptable comfort conditions only 77 percent of the time. The main, double-height hall achieves comfort conditions 39 percent of the time. In part this may be due to the volume of the space and the possible stratification of temperature, with heat rising. The infill panels of the exterior walls of this room are predominantly new insulated panels, with only 9 percent new wattle and daub. The measurements suggest that the least comfortable room is the second bedroom, located on the ground floor, which achieves comfort conditions a mere 10 percent of the time, even though 62 percent of its external infill panels are insulated and 38 percent are original lath and lime plaster. It should be noted that the effects of radiant temperature are not taken into account in these measurements.

Pressure Testing

As previously mentioned, a Minneapolis Blower Door was used to both pressurize and depressurize the building while undertaking the thermography. The same equipment was also used to undertake depressurizing to measure the air-permeability index ($m^3/hr/m^2$) and air-change rate of the house. The methodology, as prescribed by the British Standard BS EN ISO 9972:2015, is to seal all vents, drains, and fireplaces and to depressurize the building to over 50 pascals, taking readings of fan pressure and building pressure on the way up and on the way down, to afterwards calculate the air-change rate at 50 pascals.[10]

In the case of Hacton Cruck, on the first attempt on March 25, 2015, it was difficult to achieve even 4 pascals even with the fan on full power, with no blanking plate, and with all vents, drains, and fireplaces sealed. While limited in number, the readings taken would suggest that the house had an air-permeability index of 154 $m^3/hr/m^2$, an air-change rate at 50 pascals of 130 changes per hour, an estimated unpressurized air-change rate of 6.5 air changes per hour, and an effective open area of 32.6 square meters. To put this in context, 32.6 square meters is the equivalent of 19 open doors, and according to UK building regulations, new-build dwellings must achieve an air-permeability index of no more than 10 $m^3/hr/m^2$. One area responsible for these high infiltration rates has already been identified, that of the junctions between panels and timber and between those timbers themselves. However, a much more significant element contributing to this lack of air-tightness is the unlined thatched roof (Fig. 10). Thermography of this element clearly showed the difference between the unlined and the lime-plastered roofs at either end of the building.

In late October 2015 the owner of Hacton Cruck decided to improve the air-tightness of the building by lime plastering, or "torching," the central section of the ceiling. The lime-plaster finish was applied to the entire underside of the thatch except to a central square, which was left untorched to represent the original presence of a smoke hole before the construction of a chimney. The plaster was not continued right up to the ridge beam but stopped short to allow some air movement to aid in drying the external thatch. Following the completion of this work, the pressure testing was repeated. This time a maximum pressure of 11 pascals was achieved. While not the 50 pascals required by the official methodology, it was an improvement. The increased pressure allowed for more readings to be taken, leading to a greater reliability of the results. These showed an air-permeability index of 80 $m^3/hr/m^2$, an air-change rate at 50 pascals of 68 changes per hour, an estimated unpressurized air-change rate of 3.4 air changes per hour, and an effective open area of 15.8 square meters. Even with the uncertainty about the accuracy of the original measurements due to the limited readings, the results of the second pres-

Fig. 10. Hacton Cruck Hall, interior view of central hall with bedroom beyond showing unlined thatch roof, 2015.

sure test show a marked improvement of approximately 50 percent.

Visitors' Perceptions and Comments

Empirical data can provide only a partial indication of the building's performance, with most measurements being only a snapshot, both in time and of one specific parameter. In order to gain a greater understanding of the comfort perceived by occupants, it is necessary to obtain the opinion of the building's users. Since Hacton Cruck is a holiday-rental property, the visitors' book provided valuable insight into guests' perceptions. Of the 135 guests who had written in the book between the opening in August 2011 and March 2016, a total of 15 percent had commented on the house being cold and drafty, and 5 percent had commented on its being warm. The other 80 percent made no mention of thermal comfort within the house, commenting instead on their delight of staying in a fourteenth-century cruck hall and the quality of the restoration work. Some of the comments concerning comfort, however, included such statements as "The authentic indoor weather provided proper gusts of wind, rather than the mere drafts of other old homes" and "far less [chilly] than one might expect from a 500-year-old medieval hall!" It is also interesting to note that a number of comments stated that the second ground-floor bedroom was the warmest. These comments are in contrast to the empirical data, which shows this room to be the coldest. Possible explanations include the radiant underfloor heating, as neither radiant nor globe temperature was monitored, and reduced drafts, as this room is on the ground floor and therefore not open to the thatched roof. These are, however, only hypotheses and require further investigation.

Conclusions and Areas for Further Study

This study demonstrates just some of the complexities inherent in the retrofit of historic timber-frame buildings. Specific results show that the existing lath-and-lime plaster has a U-value of 2.5W/m^{2}K, that the new wattle and daub has a U-value of 3.3W/m^{2}K, and that a modern infill with multi-foil insulation has a U-value of 0.7W/m^{2}K, thereby allowing transmittance of only 28 percent of the heat through the historic lath-and-lime plaster panel. This analysis clearly illustrates that the inclusion of modern insulation materials within replacement infill panels can significantly improve the thermal performance of these building elements. The question, however, still remains as to whether the introduction of these materials could have unintentional negative impacts on the surrounding historic fabric through an increase in moisture content in the panel and through the creation of interstitial-hygrothermal conditions favorable to fungi or insects. As part of the wider PhD research studying the low-carbon retrofitting of historic timber-framed buildings, digital simulation of similar infill panels has been conducted, and physicals test cells are to be built, thanks to the support of the Association for Preservation Technology's Martin Weaver Scholarship.[11]

At the same time, both the thermography and pressure testing have highlighted the need for a whole-building approach when considering any energy retrofits, whether it be to contemporary or historic buildings. The initial pressure testing suggested an estimated 6.5 air changes per hour at atmospheric pressure, with an effective open area of 32.6 square meters, due to the poor airtightness of joints and the unlined thatched roof. Following the lime-plastering of the thatched roof, the subsequent pressure test showed a substantial improvement with a reduction to an estimated 3.4 air changes per hour at atmospheric pressure and an effective open area of 15.8 square meters, a reduction of approximately 50 percent. This improvement in airtightness is undeniably a step in the right direction; however, even at this reduced rate, these air changes greatly reduce any positive impact that the improved thermal transmittance of the walls might have on internal hygrothermal-comfort conditions. Research and practice concerned with improving both the energy performance and internal comfort of historic buildings must therefore look at strategies for all aspects of a building's performance and not concentrate on only individual elements.

The work by others at Hacton Cruck has saved a building that was largely ignored in the twentieth century and enabled visitors to experience the pleasure of staying in a fourteenth-century home. It is hoped that the research presented here and the owners' continuing commitment to the conservation of the building will allow the enjoyment of this building and others like it to continue for centuries to come.

Acknowledgements

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Oriel Prizeman *trained at Cambridge and the Architectural Association (UK). Having run her own practice from 1996 to 2012, she established an MSc in Sustainable Building Conservation program at Cardiff University in 2013. She has published two books and was elected to the Board of Directors of APT in November 2015. She may be reached at PrizemanO@cardiff.ac.uk.*

Notes

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